Mach cone Phenomenology: Some considerations

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With B.Betz,J.Noronha,M.Gyulassy,V.Greco

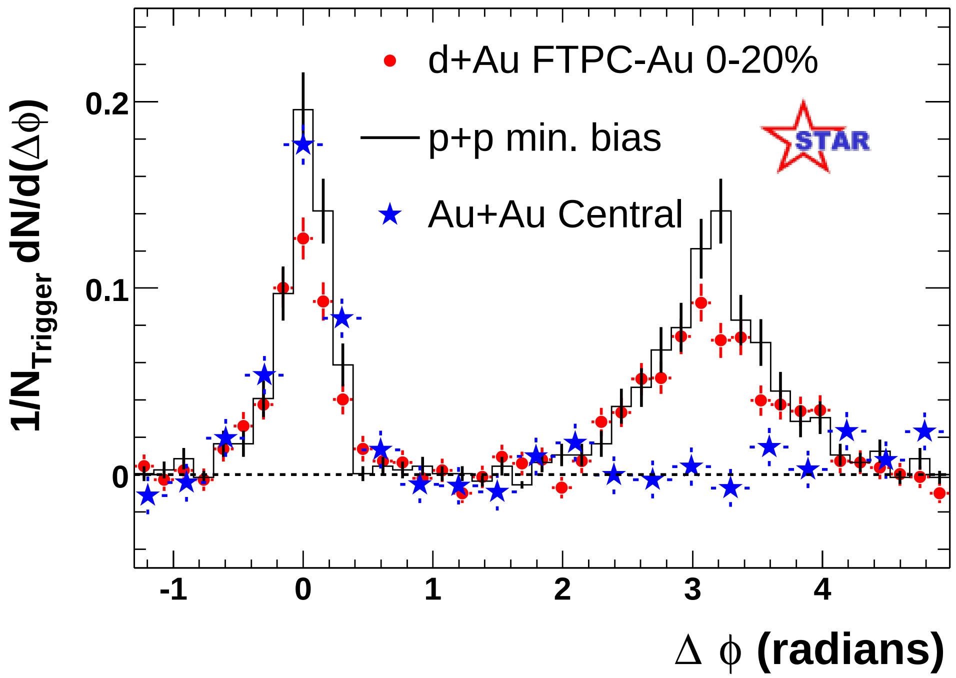
The purpose of this talk

- Draw attention to some points which, in my opinion, are
  - Not yet properly understood
  - Need to be understood if we are to understand weather conical flow exists or not

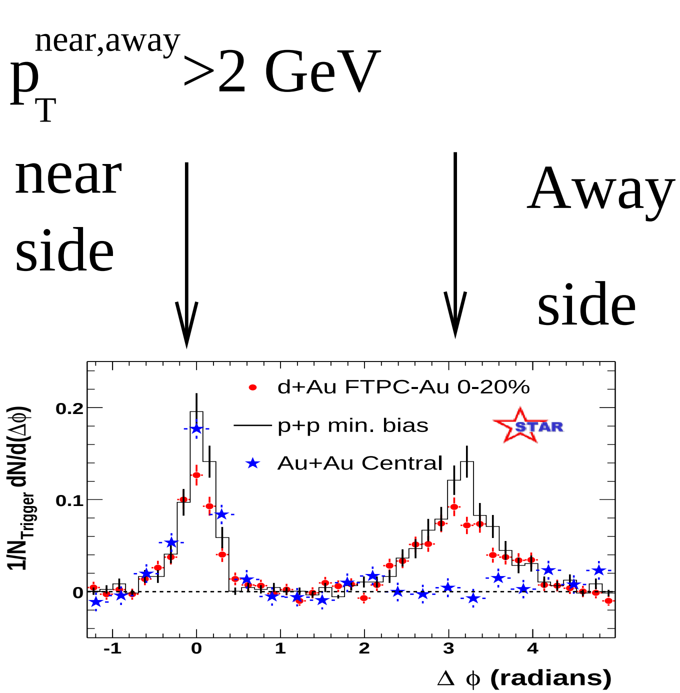
- Suggest experimental observables that could resolve these points

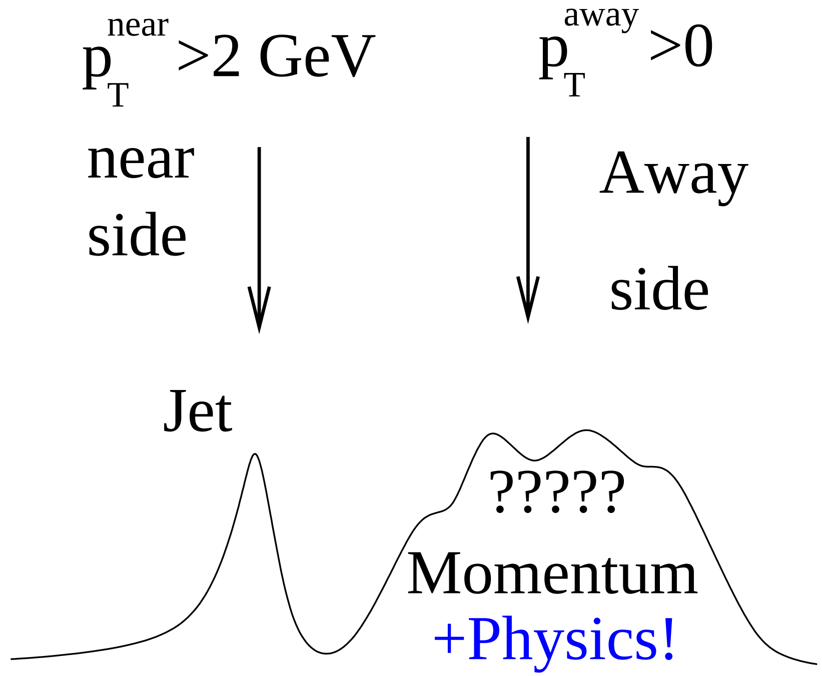
I will try to concentrate on "Joe the Plumber physics", where we can connect data to "Mach cone" theory qualitatively intependently on the (MANY) technical details the Cone could have. I will also suggest experimental measurements (some done some in progress) that test the "heart" of this physics

Exhibit I: "jets" of fast particles quickly lose energy by medium-induced radiation. This was conclusively shown to happen, and is usually interpreted as the system at RHIC being very opaque. Where does the missing E/p go?



Jet suppression revisited: Softening the away−side trigger

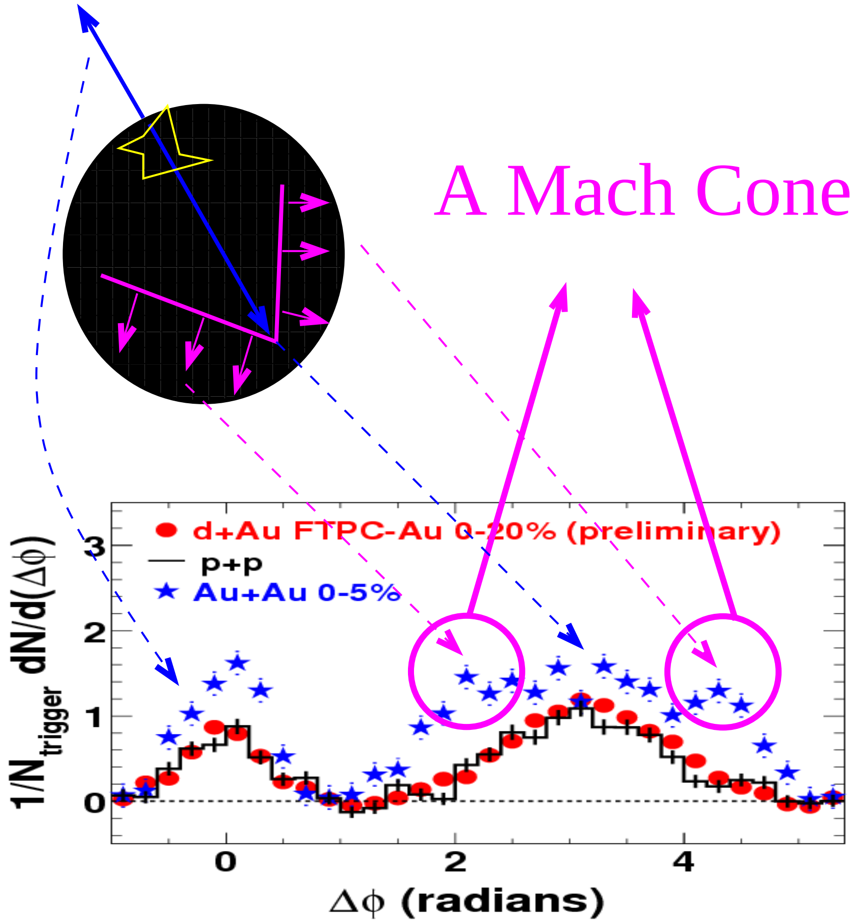




Correlations between <u>hard</u> particles ($p_T^{near,away} > 2$ GeV) suppressed. By conservation of momentum correlation should <u>reappear</u> when p_T^{away} lowered, hopefully with interesting structures!

Experiment:If we lower trigger, away-side peak reappears and...

A Mach Cone?



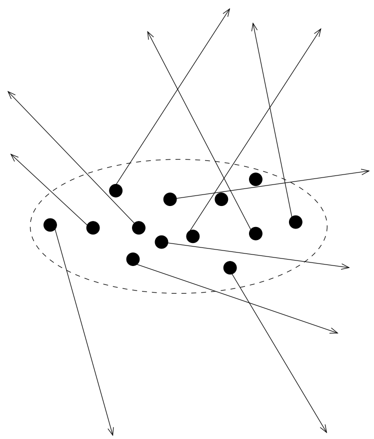
Plot from STAR
(PHENIX similar)

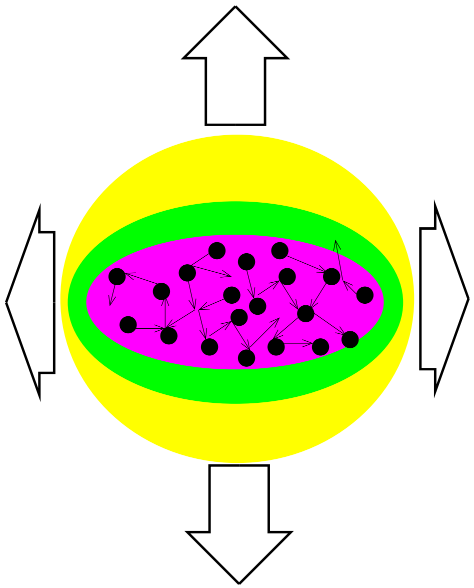
Why wed like it to be a Mach cone:

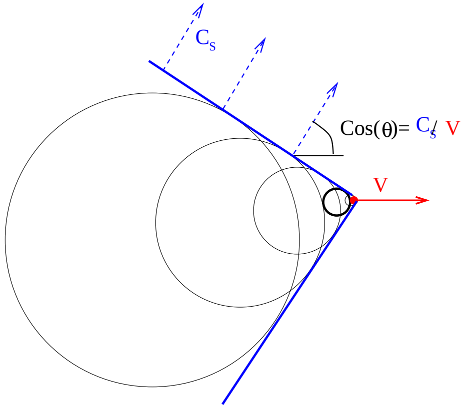
Exhibit II: v_2 suggests that the soft degrees of freedom in the RHIC system are thermalized and viscosity is low

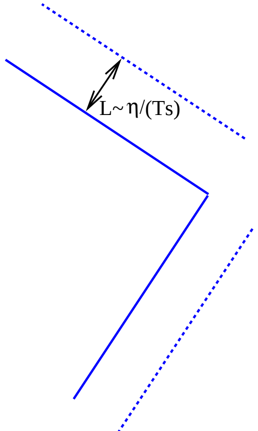
A "dust"
Particles ignore each other, their path is independent of initial shape

A "fluid"
Particles continuously interact. Expansion determined by density gradient (shape)









Mach cone angle Sensitive to EoS, $\cos\theta = c_s/v$

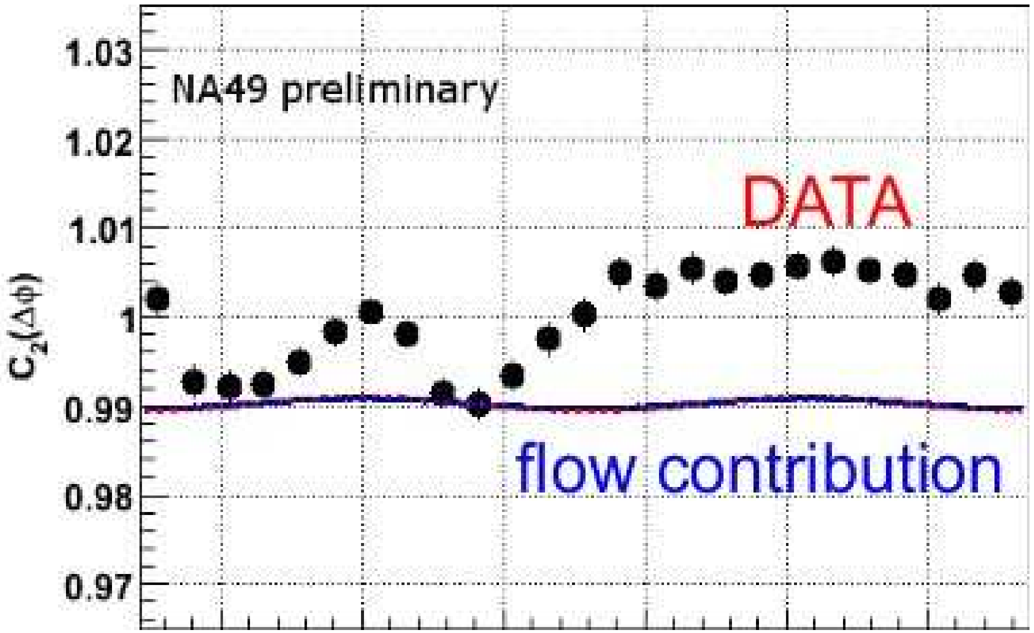
Cone killed by high viscosity exponentially, $A(x) \sim A(0)e^{-x/\Gamma}, \Gamma \sim \eta/(Ts)$

IF we see this, we confirm fast thermalization and study fluid's EoS!

Does the Mach cone fit with the "perfect fluid at RHIC" theory?

CERES (20 GeV SPS): Mach cone signal clearer! (same angle)

M.Szuba (NA49) 0-5 % HQ2008



Heinz+Kolb

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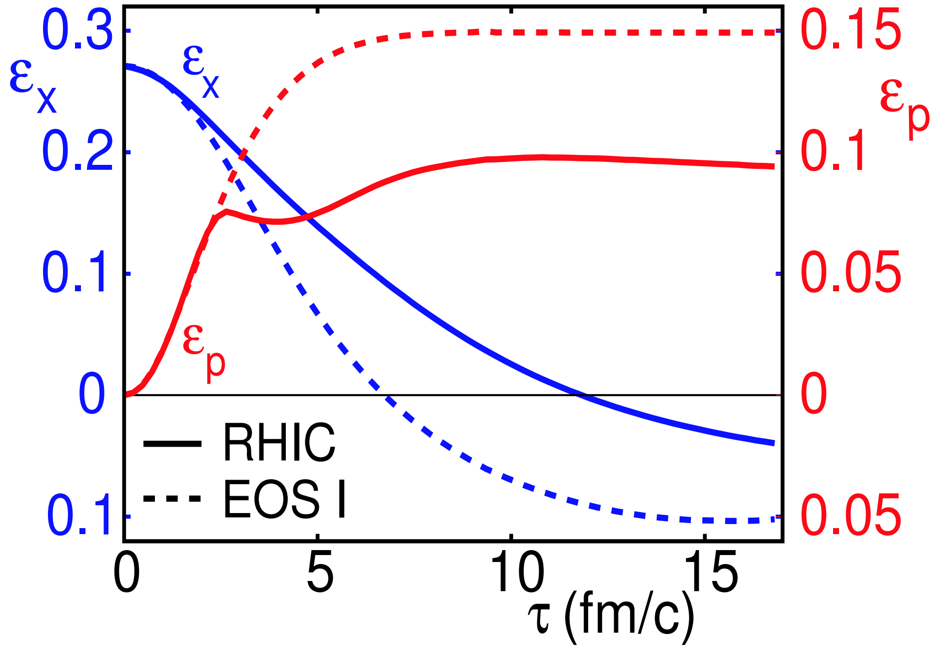
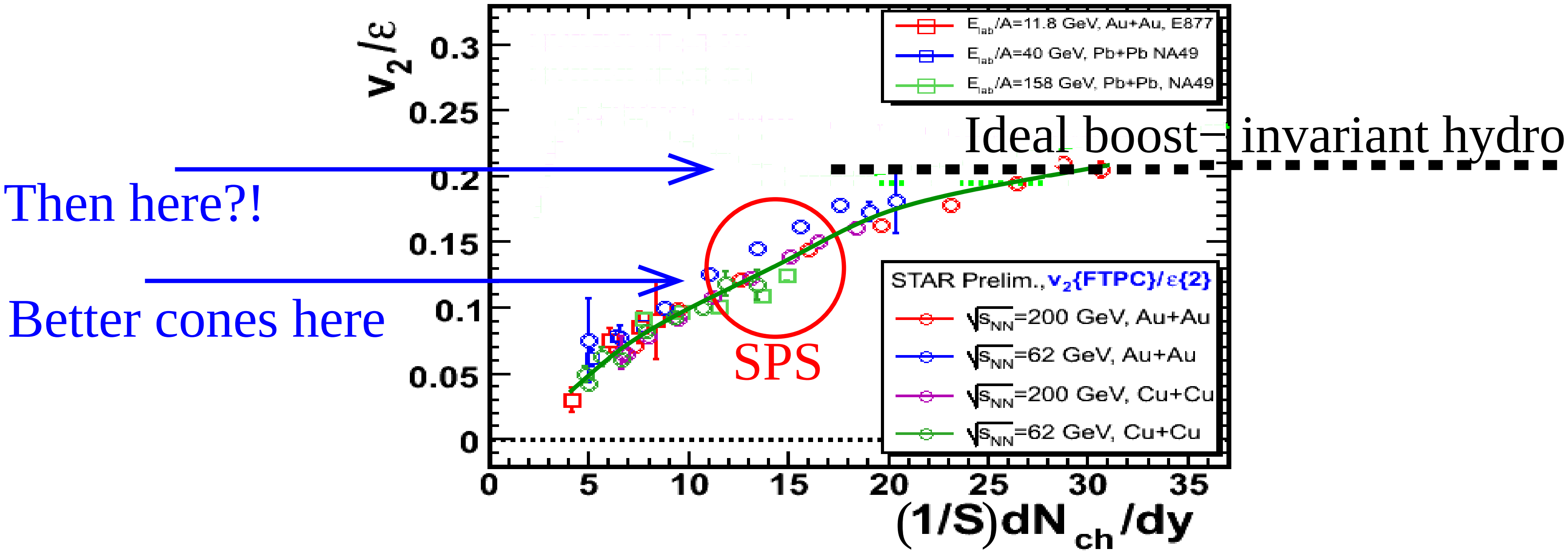


Scale of formation of v_2 comparable to Mach cone's formation time. Thus, both form at the $\sim T >> T_f$. Mach cone appearance should "mimic" v_2, but should be worse as "Knudsen number" of Mach system, $Kn = \frac{l_{mfp}}{R} \sim l_{mfp} \partial u$(size compared to mean free path) is larger.

So This is weird



Either we do not understand Mach cones or we do not understand v_2. Lets start from the former hypothesis

What could this be (Hopefully an exhaustive list)?

A Mach cone In the "traditional" sense

A "non-mach" cone A non-equilibrated and/or non-linear structure nearby to the quark

A physical mis-understanding of background Is ZYAM physically sound?

An effect of coalescence Why not here?

An effect of resonance decays Coalescence "in reverse"

Deflected jets and Cherenkov Examined elsewhere, bar some considerations

And how could we tell!

Why linearized hydrodynamics+

Cooper-Frye will generally <u>not</u> give you a cone

The bad news: If hydro linearized (Including AdS/CFT), double peak cone structure smeared away by freeze-out. If $u_{cone\ \ flow} = (u_{jet}, u_\perp)$,$\Sigma = (1, \vec{0})$,

$$\frac{dN}{p_T dp_T d\phi}|_{y=0} = \int_{\Sigma_T} d\Sigma_\mu P^\mu \left[f(U^\mu, P^\mu, T) - f_{eq}\left(P^0, T_0\right)\right]$$

Background $\vec{U} = 0, T = T_0$, cone $\vec{U} = (U_\perp, U_L), \Sigma^\mu = (1, \vec{0})$ (Isochronous)

$$f(\phi) = 2\pi\, p_T \int_{\Sigma_\perp} dx_1 dx_\perp x_\perp \times \left(\exp\left\{ -\frac{p_T}{T}\left[U_0 - U_1 \cos(\pi - \phi)\right]\right\} I_0(a_\perp) - e^{-p_T/T_0} \right)$$

expanding Bessel function to first order in $p_\perp U_\perp / T$ we get

$$f(\phi) \simeq e^{-p_\perp/T_0} \frac{2\pi\, p_\perp^2}{T_0} \left[\frac{\langle \Delta T \rangle}{T_0} + \langle U_1 \rangle \underbrace{\cos(\pi - \phi)}_{One\quad Peak\quad :(} \right]$$

(Transverse flow? We will see, but v_T forms <u>later</u>)

Bottom line:Either non-linear corrections big (but then not true "Mach cone", wait a few transparencies and See Jorge's talk) or $p_T >> T$ (but then when does particle stop being thermal?)

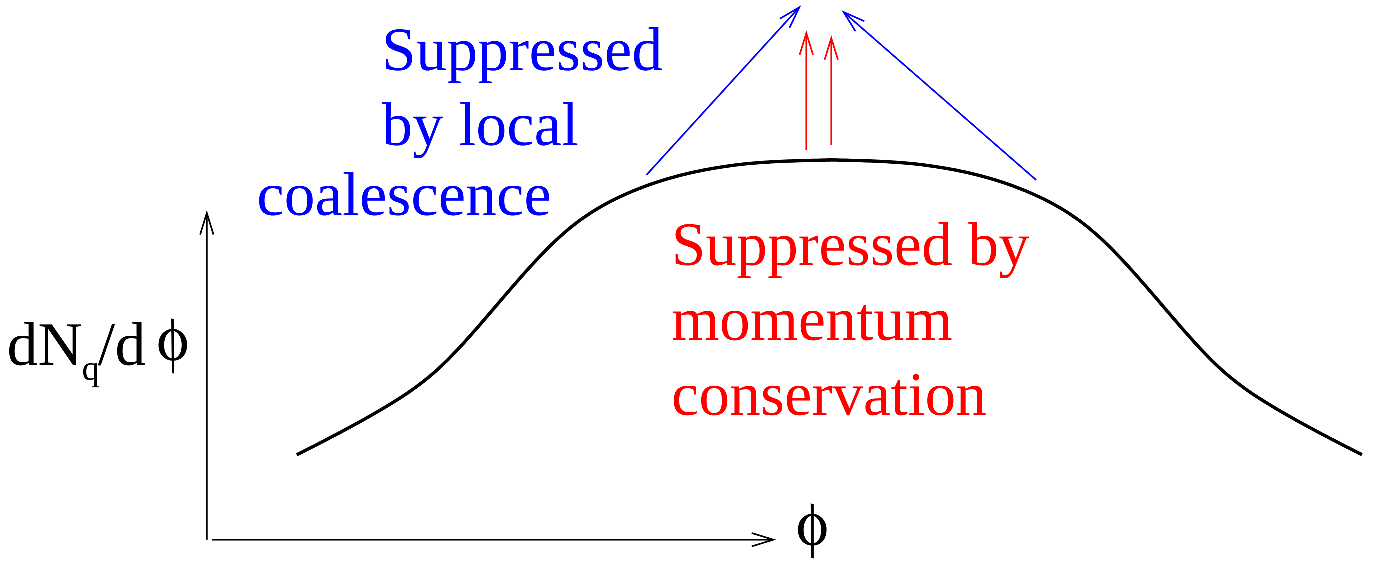
Bottom line: Cone signal <u>unavoidably</u> in a momentum scale where things like coalescence <u>expected</u> to be relevant. Studying its effects crucial

Coalescence could save us! If coalescence non-collinear ($m_q \sim T$)+local

$$\frac{dN}{d^3p} = \prod_i \int (d^3 p_i) \int (d^3 x_i) \left[\prod_i f(\vec{p}_i, \vec{x}_i) \right] \delta \left(\vec{p}_h - \sum_i \vec{p}_i \right) \underbrace{\prod_{i,j} W\left(\vec{x}_i - \vec{x}_j \right)}_{local}$$

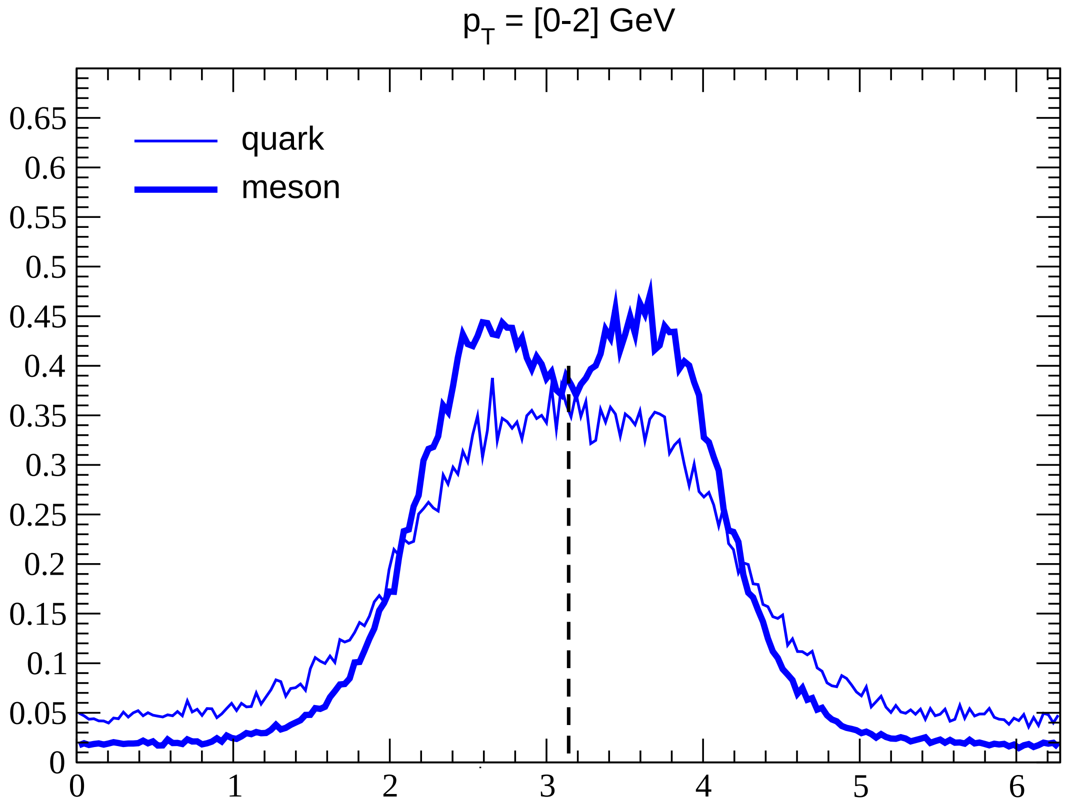
Conical signal (Cone, wake,...) has cylindrical symmetry around jet direction, so $u_\perp \sim \varphi_{conf.space}$

The locality in φ, and the fact that in a conical solution $\vec{u}$ in the radial direction means peak $\longrightarrow$ Peak coalescence suppressed.



1 Peak+ coalescence $\longrightarrow$ 2-peaks! (not cone, angle $\leftrightarrow$ dynamics,not EoS!
"Cone" for Mesons and baryons will be different!

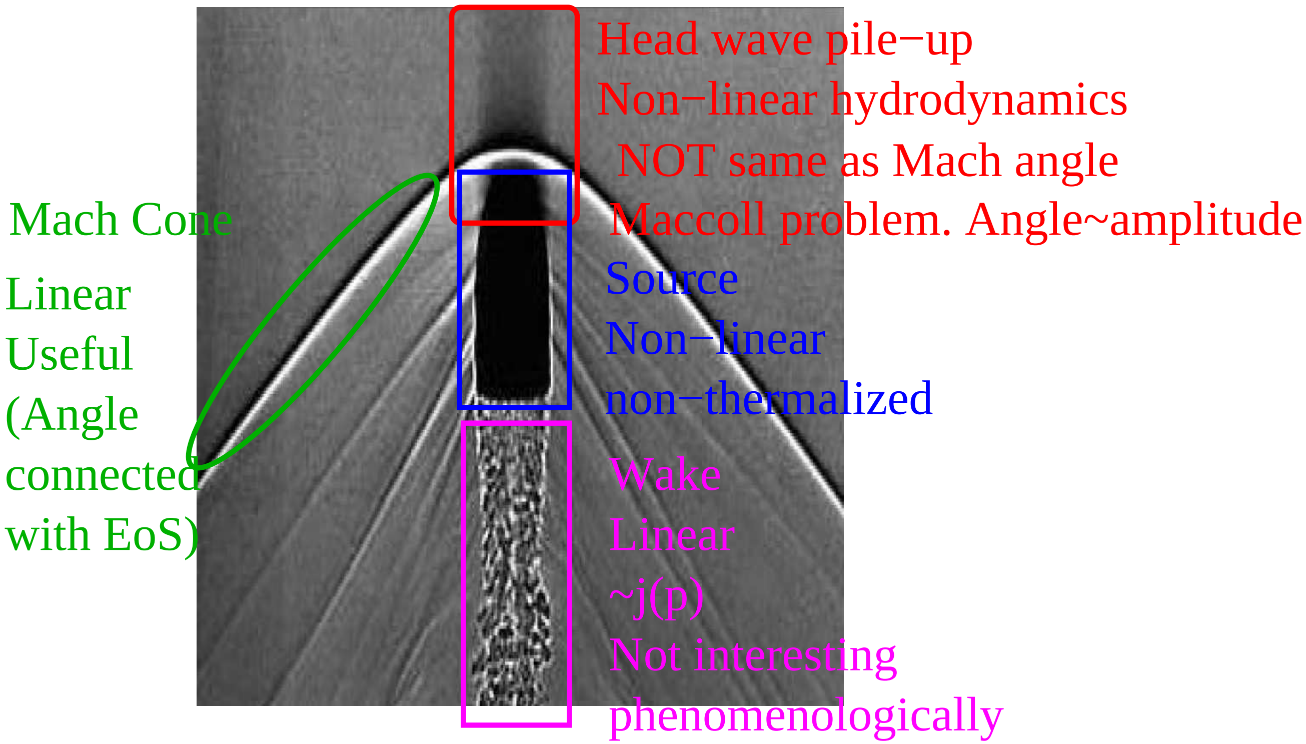
Very preliminary (See QM for full story)...

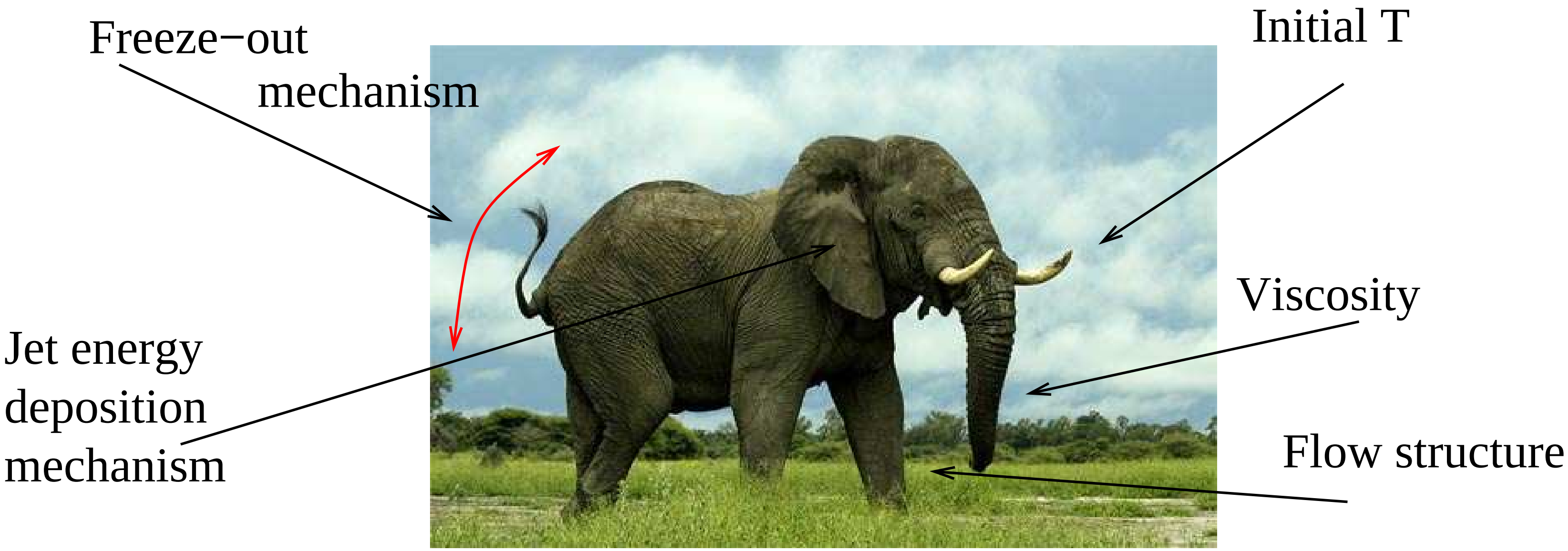


Is it true? p vs π Mach cone <u>crucial</u>.

Why Mach cones are more complicated than we might hope

Bad news II: Mach cone itself is a complicated object. Which of these parts dominates conical signal?





My worry...

What is the predictivity of the statement "energy lost to jets is quickly thermalized and becomes hydrodynamic excitations"?

(Mach cones are a likely consequence)

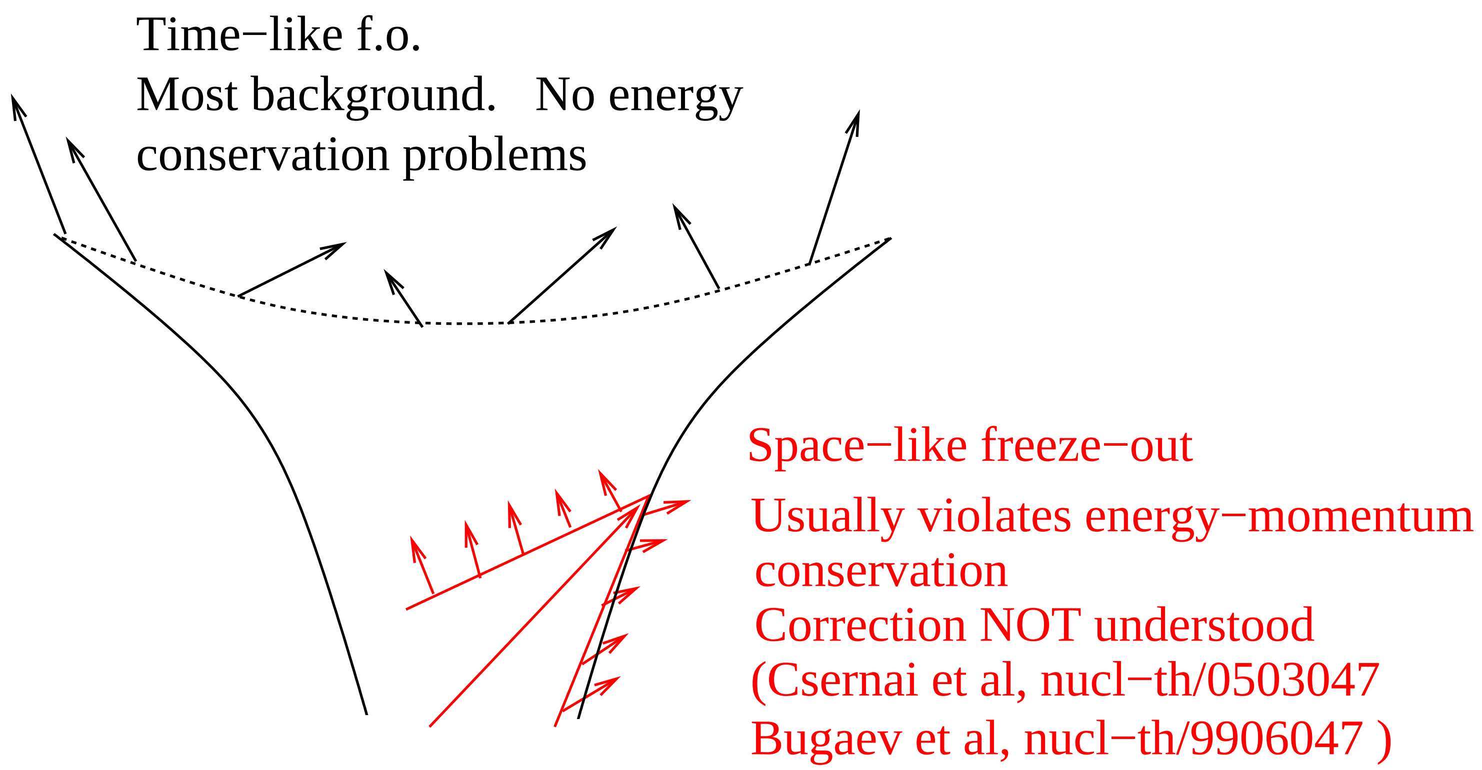
Eg: A misconception

In Hydro,unlike in Cherenkov, the Mach cone angle does not depend on p_T.
Unless freeze-out is not Cooper-Frye, this is generally NOT the case

$$E\frac{dN}{d^3p} = \int \underbrace{p_\mu d\Sigma^\mu}_{\sim \frac{dt_f}{dr} p_T} f_{FD/BE}(\underbrace{p_\mu u^\mu}_{\sim v_T p_T}, T, \mu_B)$$

In general $v_T p_T \neq \frac{dt_f}{dr} p_T$ ($v_T \ll 1$ for linearized conical flow), and <u>both</u> t_f <u>as well</u> as v_T exhibit a conical excitation. <u>If</u> freeze-out is isothermal, or Iso-Knudsen (Ala Dusling+Teaney), or iso-any local criterion, you should get a (perhaps small but finite) dependence of the angle on p_T. <u>only</u> if freeze-out is Isochronous (unphysical!) it disappears.
More generally, ideal hydro+freeze-out <u>still have</u> quite a few parameters that <u>potentially</u> could alter the Mach signal <u>significantly</u>

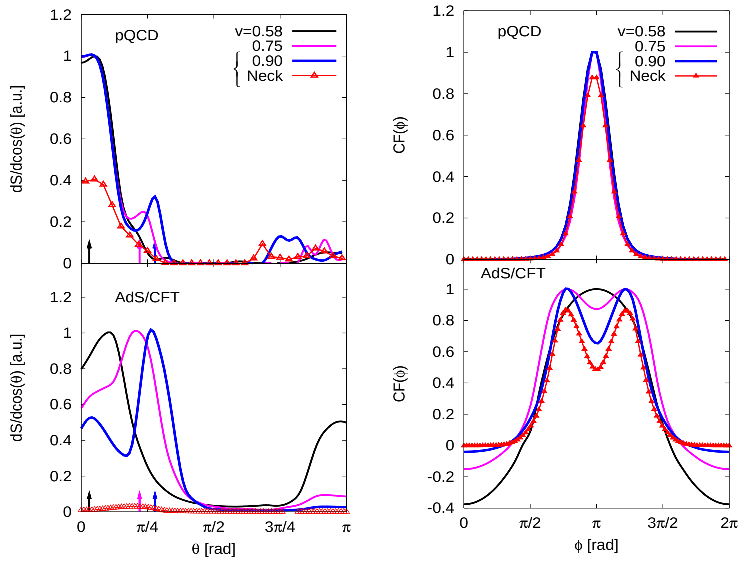
Bad news III: Mach cones sensitive to potentially misunderstood F.O. details



Because $d\Sigma_\mu p^\mu$ could be < 0 in space-like $(dt/dr > 0)$ region, Cooper-Frye needs fix. A lot of Mach signal could be in this region

A proposal for reducing freeze-out dependence

Measure Poynting vector, rather than particle number correlations (ie, weight by P_T!). Since Energy-Momentum is conserved, it might be less dependent on not understood F.O. dynamics



0812.1905
B Betz, J Noronha, M Gyulassy, GT

Systematic comparison, Cooper−Frye vs "Bowling ball", AdS/CFT vs pQCD solutions

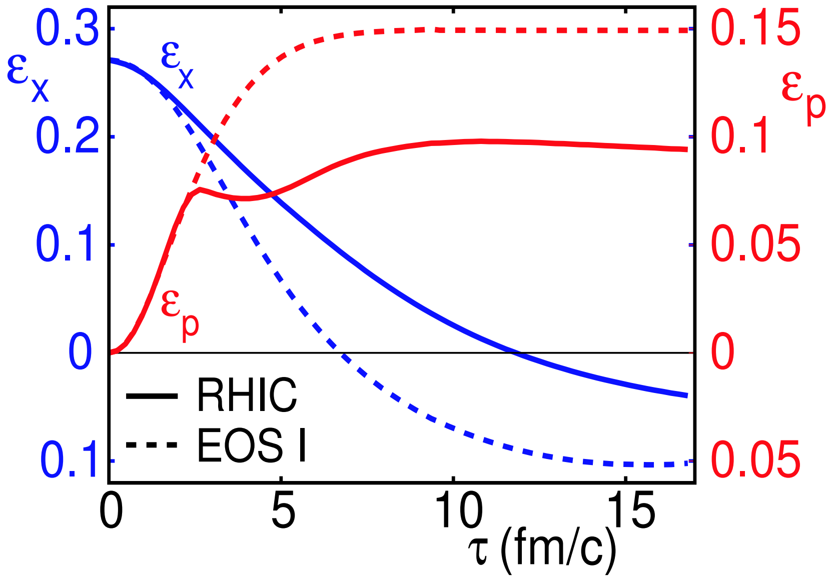
Little qualitative difference in both cases but...

A model indipendent Mach effect?

Mach cone falsification from flow?

Heinz+Kolb

nucl−th/0305084

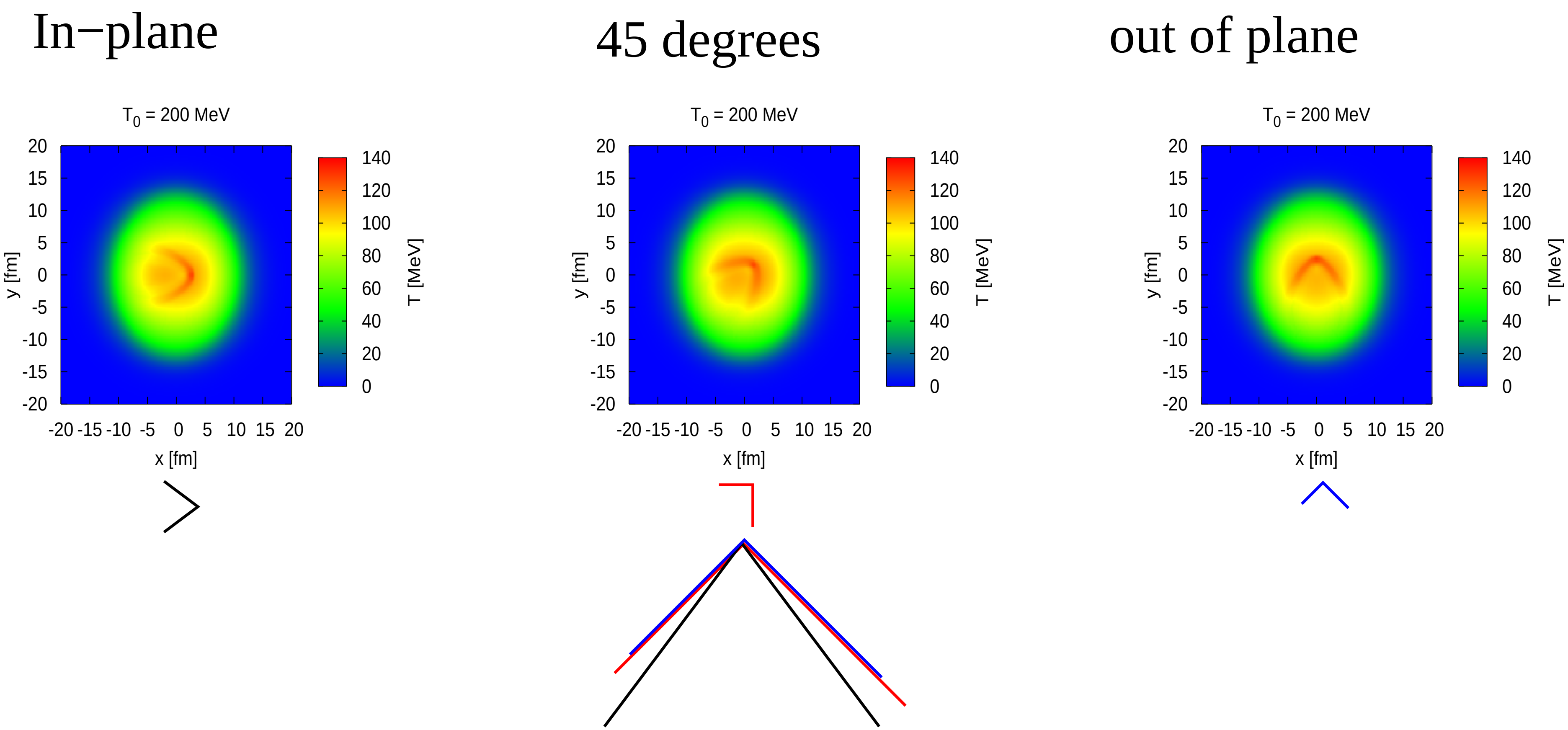


Scale of formation of v_2 comparable to Mach cone's formation time. Mach cone should feel v_2

Effect of flow : Usual relationships with frame co-moving with flow (Satarov, Stoecker,Mishustin,PLB627(2005))
In linearized limit, for ultrarelativistic jet
$\theta = \sin^{-1}\left(c_s / v_{jet}^{comoving \quad frame} \right) \rightarrow \sin^{-1}\left(c_s \sqrt{\frac{1-v^2}{1-v^2 c_s^2}} \right)$
flow $\vec{v}$, given by global hydrodynamics, narrows cone.

For $\langle v \rangle = 0.5, \delta v|_{v2} = 10\%$ we have a $\simeq 0.1$ radians difference, accessible to experiment. This qualitative effect is a model-independent proof of "true Mach-conness". If its a linear sound-wave, it should be sensitive to background flow!

A "cursory" full hydro calculation confirms difference <u>should</u> be observable
(Full results for QM!)



If the Mach cone is not sensitive to flow, what else can it be?

Fluids can be distinguished from non-equilibrium systems by the Knudsen number

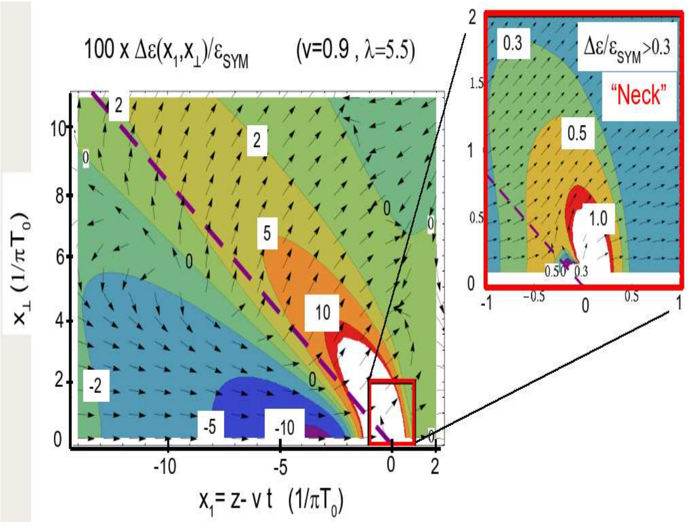
$$Kn = \frac{1}{\langle p \rangle l_{mfp}} \partial \langle p \rangle \sim \frac{\eta}{e+p} \partial u_\mu$$

$Kn \sim 0$ Sysem is a fluid

$Kn \sim 1$ System is a

- Dust if coupling is weak
- Coherent field if coupling is strong

In-between, system is an imperfect fluid (weak coupling) or a "Magneto-fluid" at strong coupling.

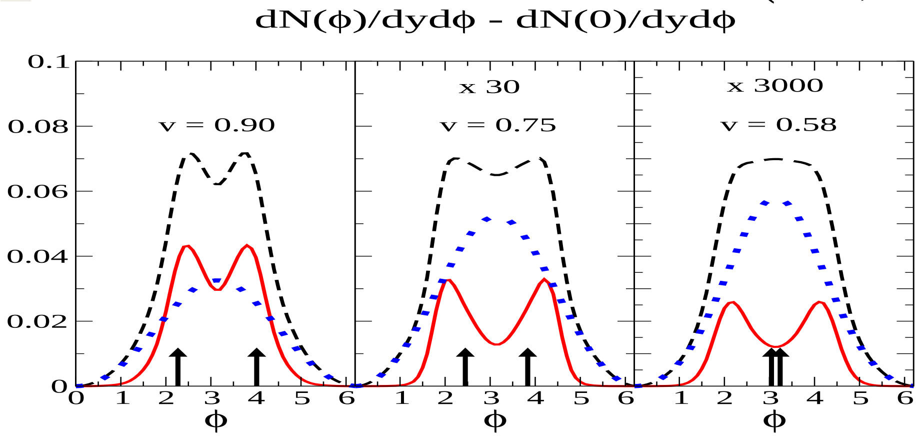


Mach: Kn>3 (~Fluid)

Neck: 3<Kn<1 (~Magneto−fluid?)

Head: Kn<1 (~Coherent field?)

Gyulassy,Noronha,GT:0807.2235
(PRL, In press)



STRONG "cone−like" signal from
NON−thermalized "neck"
BUT NOT "real" cone
does not obey Mach's law
probably less sensitive to flow

Is the cone really a Cone? If no flow sensitivity, perhaps NO!

Why I doubt ZYAM but could be convinced...

ZYAM: A theoretical perspective

$$\frac{dN}{d(\phi_{soft}-\phi_{hard})} = \underbrace{\frac{dN}{d(\phi_{soft}-\phi_{hard})}}_{Cone?} + \underbrace{A}_{Norm\quad (ZYAM)} \underbrace{\frac{dN}{d(\phi_{soft}-\phi_{hard})}}_{Flow}$$

The flow part counts the correlation coming from the fact that both soft and Hard particles are correlated (with different weights) wrt reaction plane.

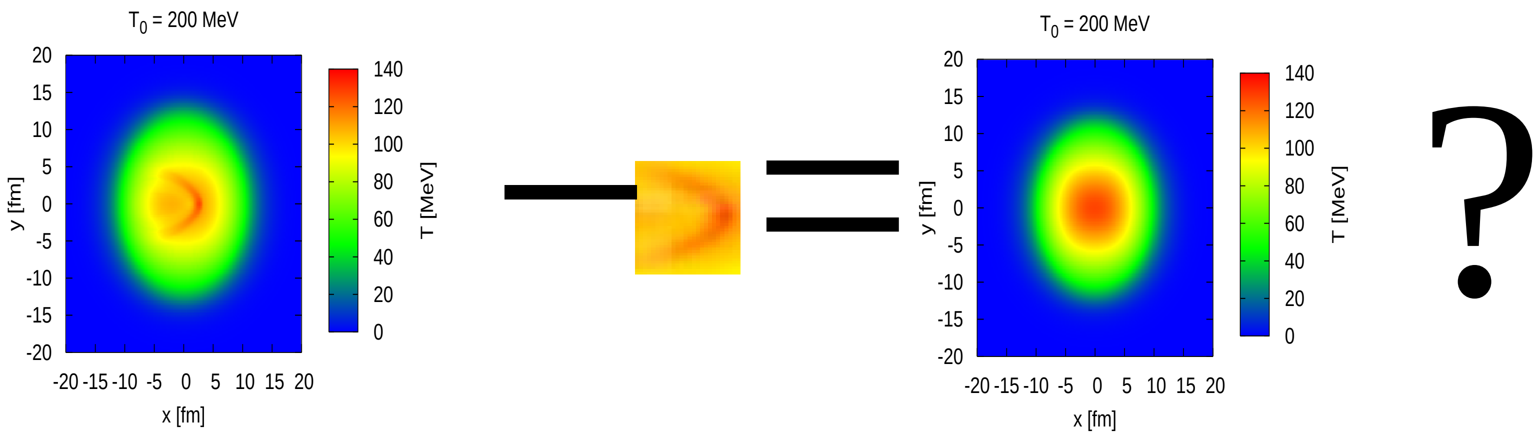
$$\underbrace{\frac{dN}{d(\phi_{soft}-\phi_{hard})}}_{Flow} = \int d(\phi_{soft}+\phi_{hard}) \left(1 + 2 \underbrace{v_2(p_T^{soft})}_{=v_2(p_T^{soft})\big|_{nojet}} \cos(2(\phi_{soft}-\phi_{reaction})) \right)$$

$$\times \left(1 + 2v_2(p_T^{hard}) \cos(2(\phi_{hard}-\phi_{reaction}))\right) \underbrace{\simeq}_{v_{n>2}=0} 1 + v_2^{soft} v_2^{hard} \cos(2(\phi_{soft}-\phi_{hard}))$$

This background subtraction contains some assumptions that are really theoretical, rather than experimental:

- That v_2 is not changed much by a presence of hard particle

- That the induced v_2 from conical flow is small.

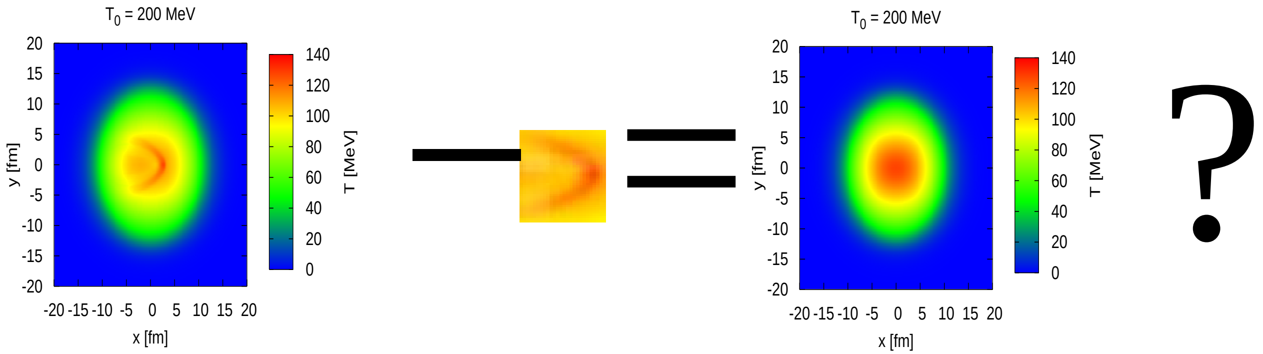


The assumptions are reasonable:

They do work for a "small" cone in linear hydrodynamics.

On the other hand, the cone is not small, and, as the ridge teaches us, soft correlations induced by hard particles can be more extensive than what is naively thought. (NB: any Harmonic of the flow influences every v_n).

Thus, current method of background subtraction is theoretically ambiguous.



Assumptions CAN be checked: Measure $\langle p_T \rangle, v_2$ separately for jetty and non-jetty samples.

Beyond correlations

Deflected jets, Cherenkov gluons, necks (?) etc. are fragmenting. Particles in Mach cone part of flowing medium.

- Fragmenting particles are typically power-law, in-medium are exponential. More flow (e.g. Mach cones) blue shifts exponential, but its still exponential

- Fragmentating particles have same chemical composition of $p - p$ collisions. Flowing particles have same chemical composition of $Au - Au$. The two are not the same! $(K/\pi, p/\pi$ ratio etc.).

This analysis done for tagged "away-side" particles could distinguish scenarios independently of not understood parameters $(J^{\mu}, non-linearity$ etc.).

Bottom line:

While the observation of the Mach cone would be great, its lack would not prove much because it depends on assumptions independent of the degree of fluidity The more general question is: Are the degrees of freedom lost by the jet thermalized?. And studies of correlation functions might not by themselves answer this!

(few) conclusions!

- Mach cone-like patterns arise in a variety of hydro-like models
- Link between features and "fundamental" physics weakened by <u>many</u> not understood parameters
- Experimentalists found <u>something that looks like a Mach cone</u>. But we are not quite certain how to interpret it within the "big RHIC picture", and say something about the medium

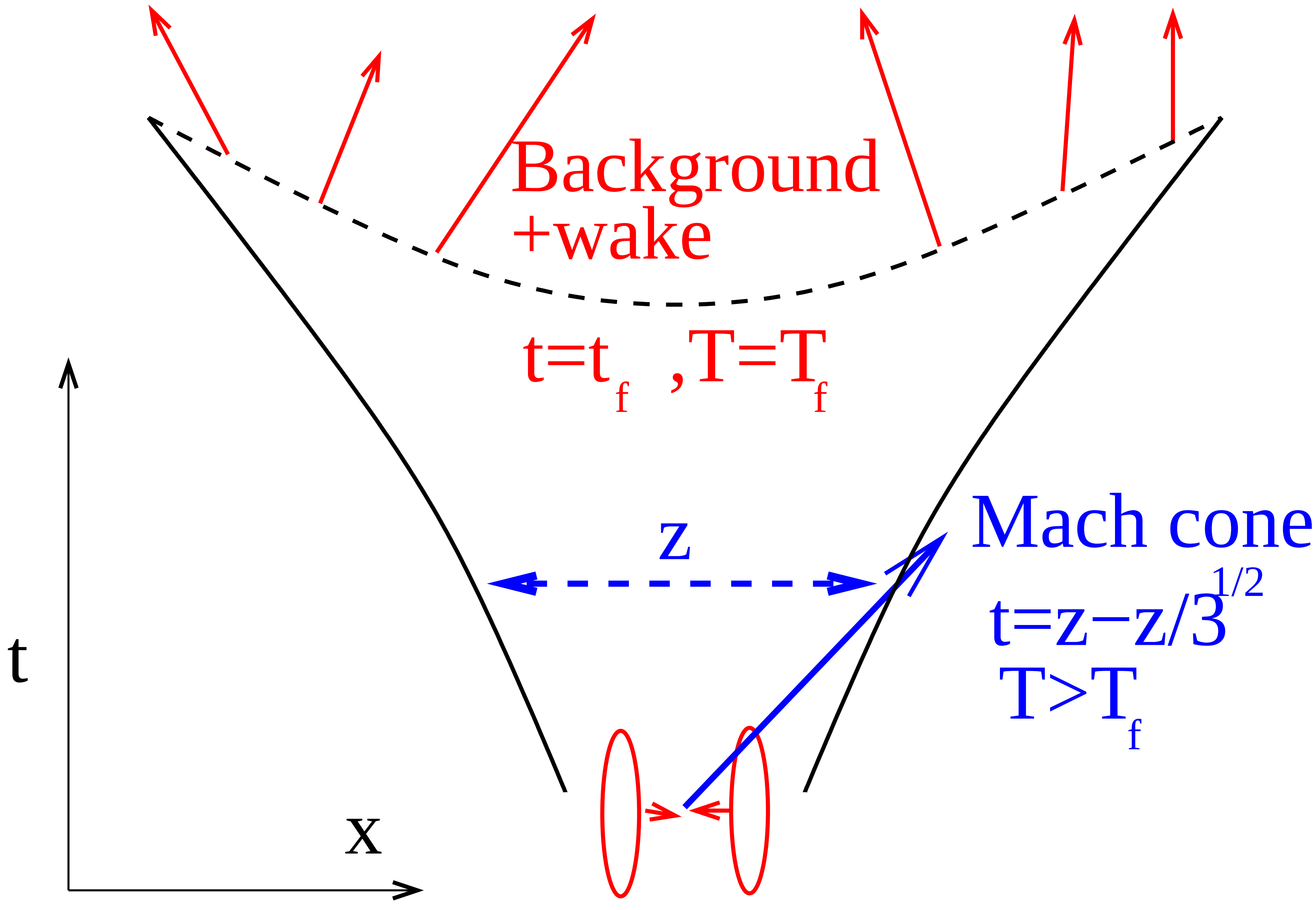
Theoretical results that could make a difference

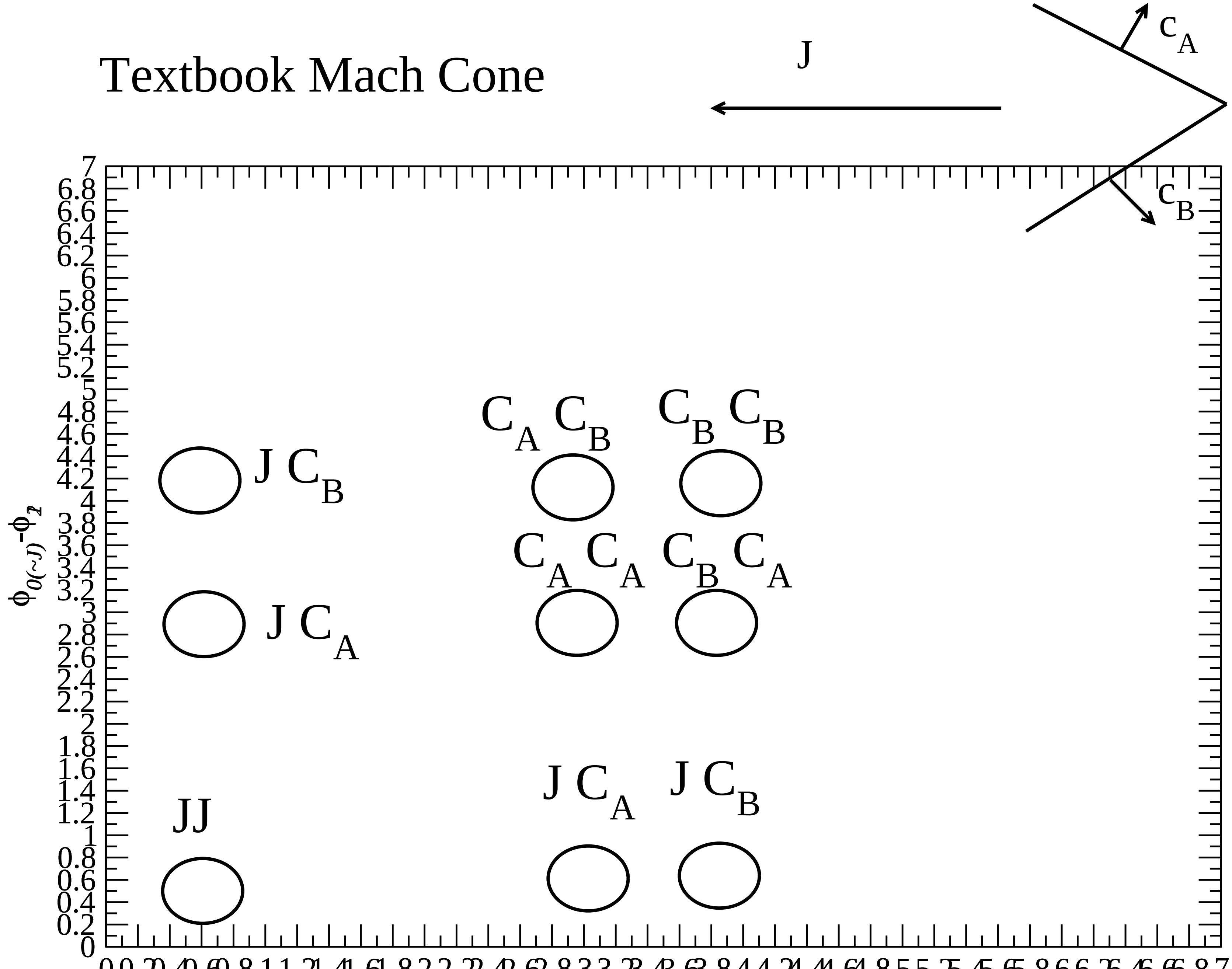
- Systematic study of deposition mechanisms
- Freeze-out(Resonances, Σ_μ)
- Different f.o. Mechanicsm

Experimental results that could make a difference

- Poynting vector correlations
- Meson vs Baryon Mach cones
- ZYAM experimental verification
- Chemical composition and thermal structure of associates. Are they "jetty" or "mediumy"?Angle dependence on system size/jet-reaction plane?

BACKUP SLIDES


Background
+wake
t=t_f ,T=T_f
Mach cone
z
t=z−z/3^{1/2}
T>T_f
t
x


Textbook Mach Cone
J
c_A
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C_A C_B
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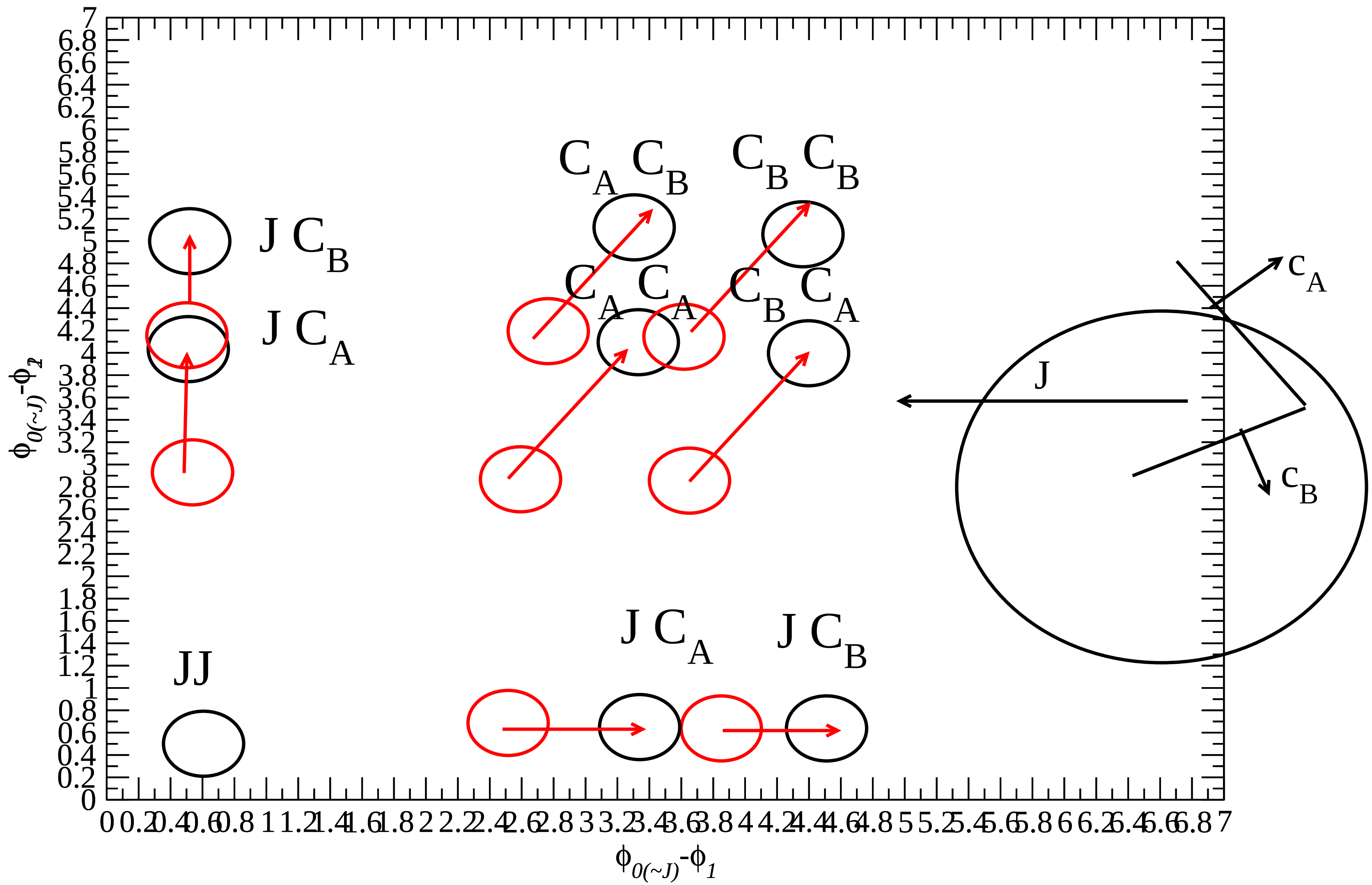
$\phi_{0(\sim J)}-\phi_2$

Flow-shifted "small" Mach Cone



Realistic deformed Mach Cone